Radiative Corrections to Higgs Production:

How accurate are our predictions?

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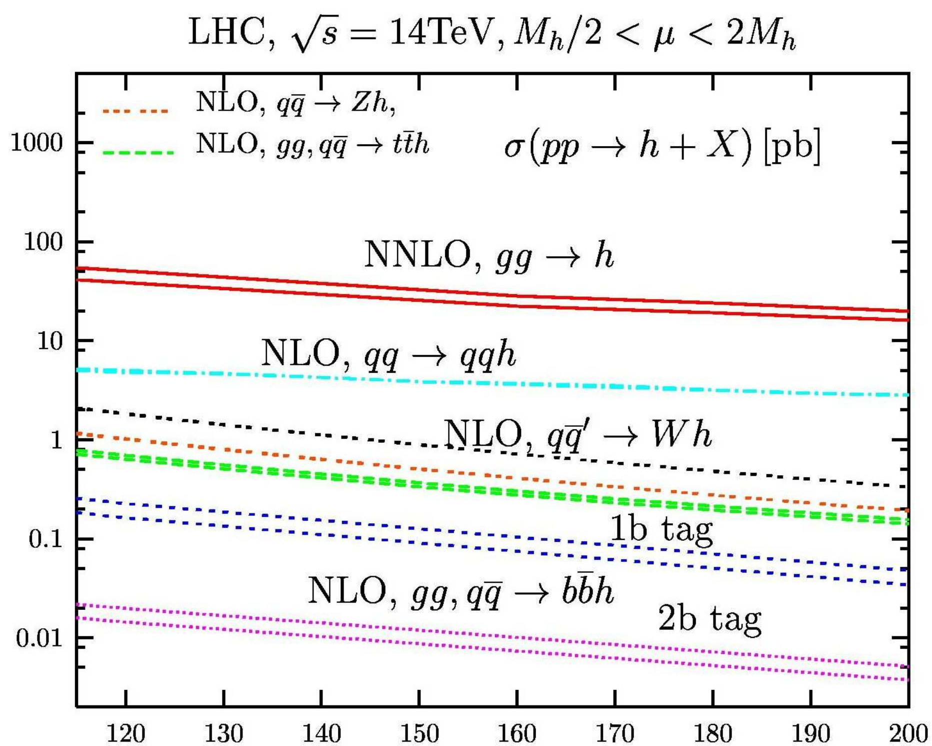
January, 2009

Higgs Production

- How well do we know cross sections?
- What assumptions go into plots?

σ (pb)

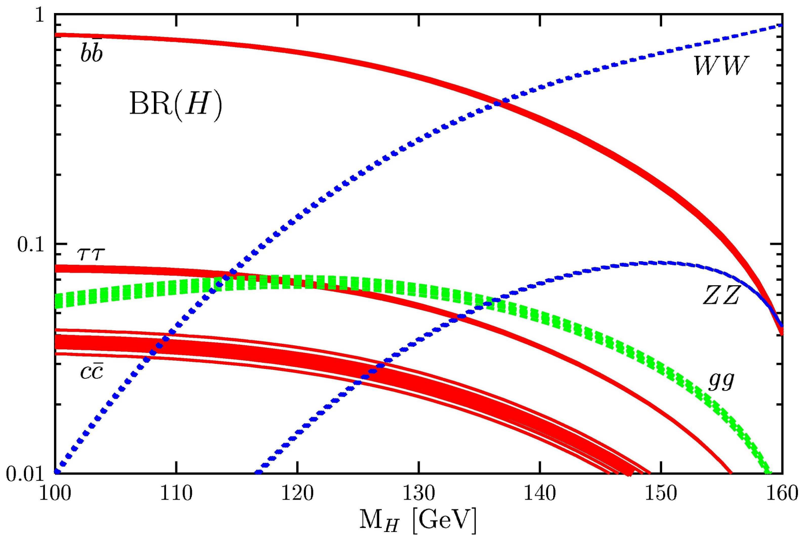


M_H (GeV)

Bands are scale dependence only in this plot

Branching Ratios

- Bands are theory uncertainty
  - Includes all known higher order corrections
  - Largest uncertainty from $m_b = 4.88 \pm .07$ GeV

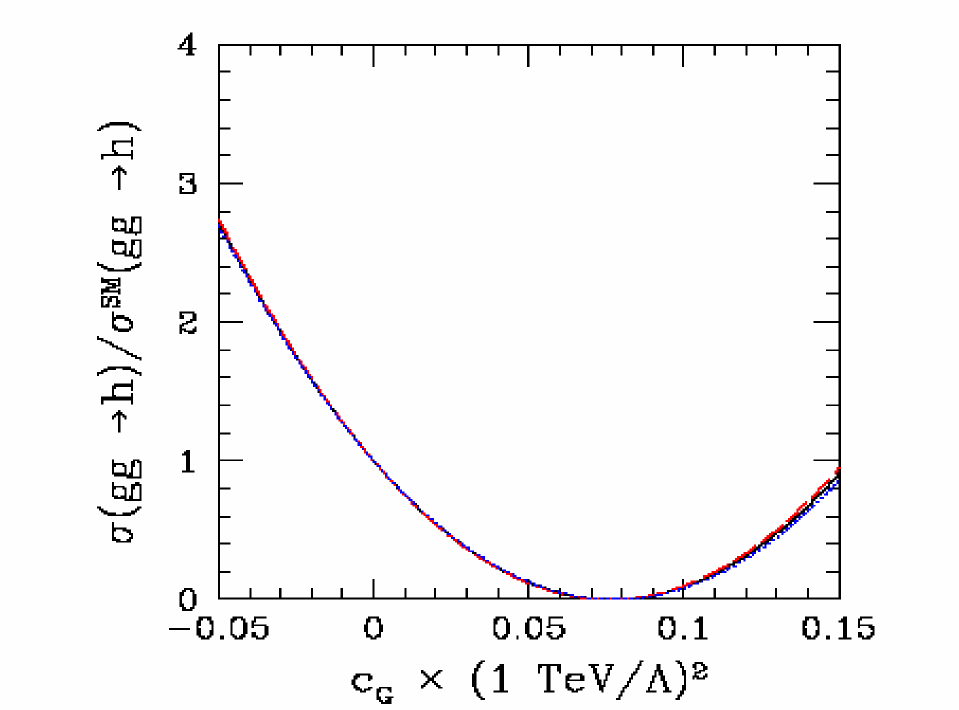


FEYNHIGGS, HDECAY include known higher order corrections

Djouadi, hep-ph/0503172

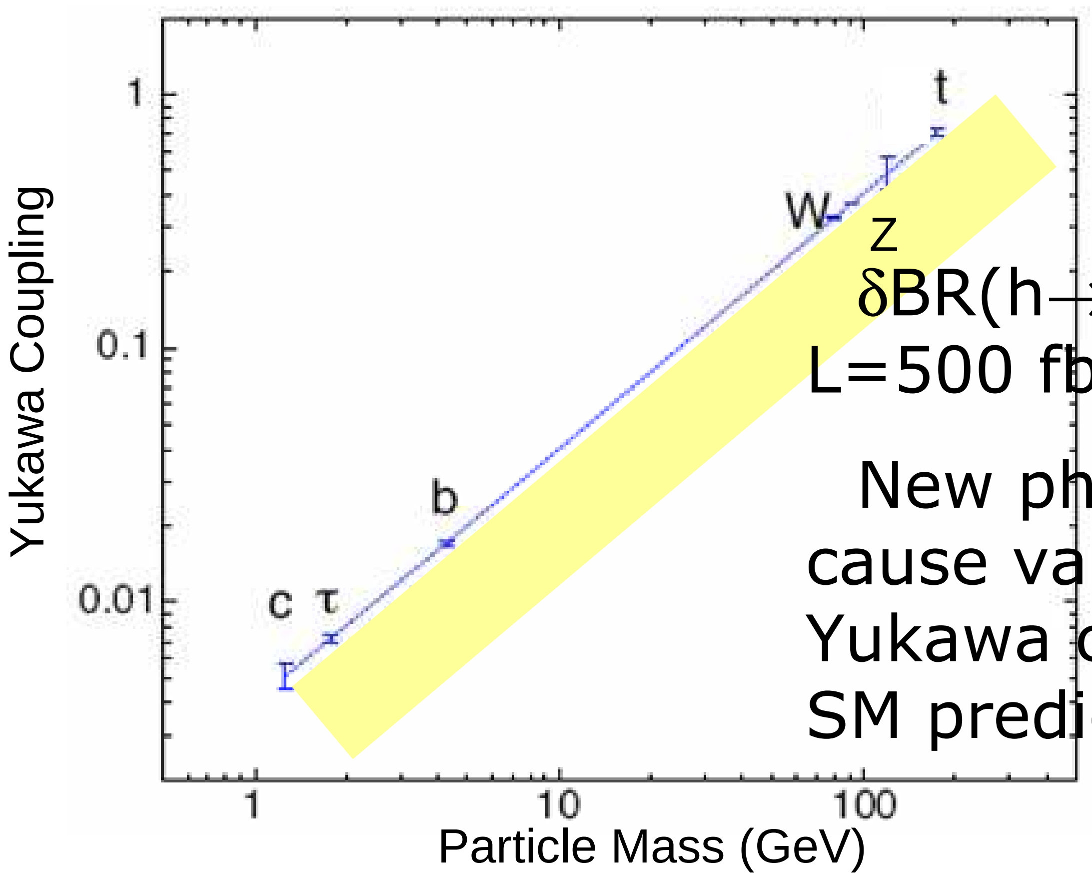
Can we use Higgs rates to distinguish between models?

$$L_{eff} = -c_g 2\pi\alpha_s \left(\frac{v}{\Lambda}\right)^2 \frac{H}{v} G^A_{\mu\nu} G^{\mu\nu A}$$



Manohar and Wise, arXiv:0601212

ILC Measurements

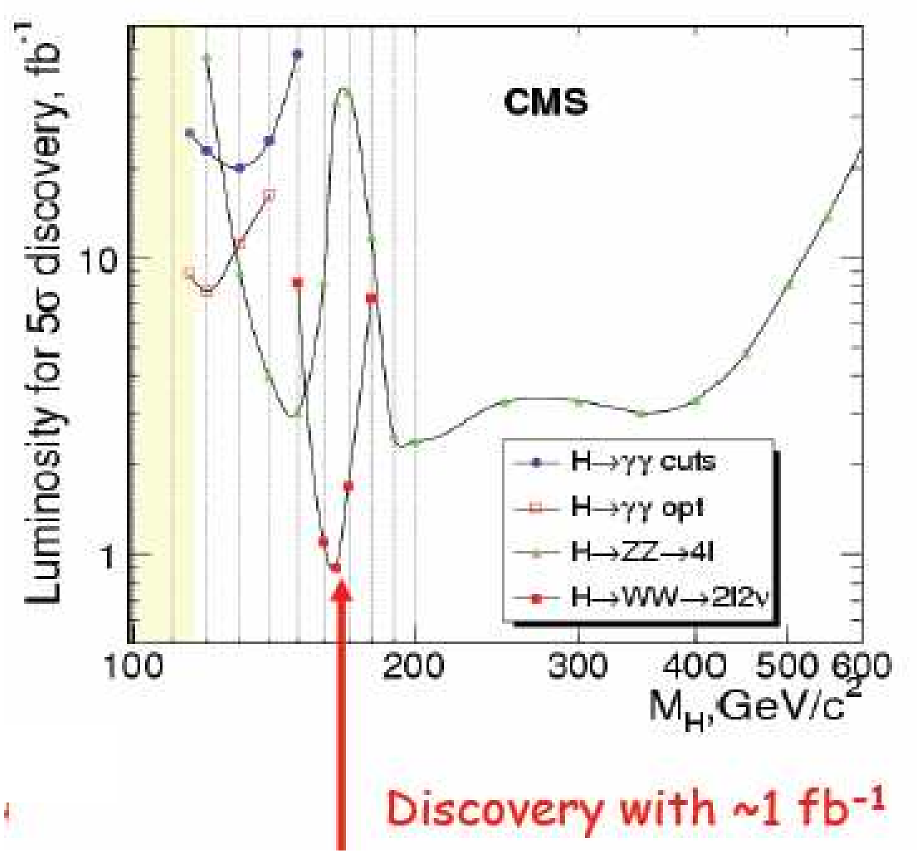


$\delta BR(h \rightarrow bb) \sim 2\%$ with L=500 fb^{-1}

New phenomena can cause variations of Yukawa couplings from SM predictions

Yellow band corresponds to new physics on the 1-5 TeV scale

CMS SM Higgs, 2008



Gluon Fusion

Largest contribution is top loop

Largest rate for all M_H at LHC

– Sensitive to top quark Yukawa λ_t

Lowest order cross section:

$$\hat{\sigma}_0(gg \to h) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2} \left| \sum_q F_{1/2}(\tau_q) \right|^2 \delta(M_h^{\ 2} - \hat{s})$$

– $\tau_q = 4M_q^2/M_H^2$

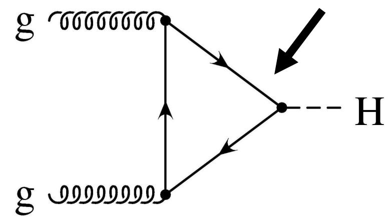
– Light Quarks:

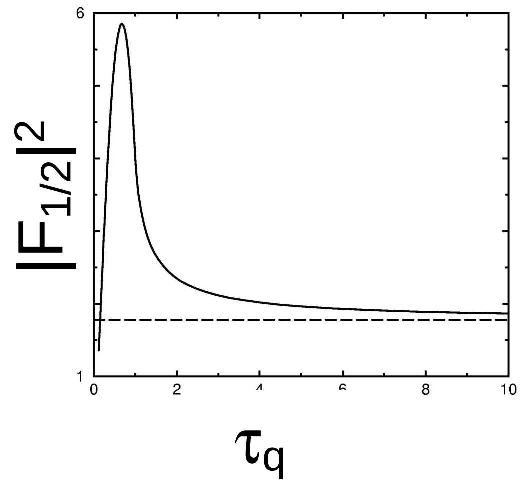
$F_{1/2} \to (M_b/M_H)^2 \log(M_b/M_H)$

– Heavy Quarks: $F_{1/2} \to -4/3$

– Counts # heavy generations

In SM, b-quark loops unimportant





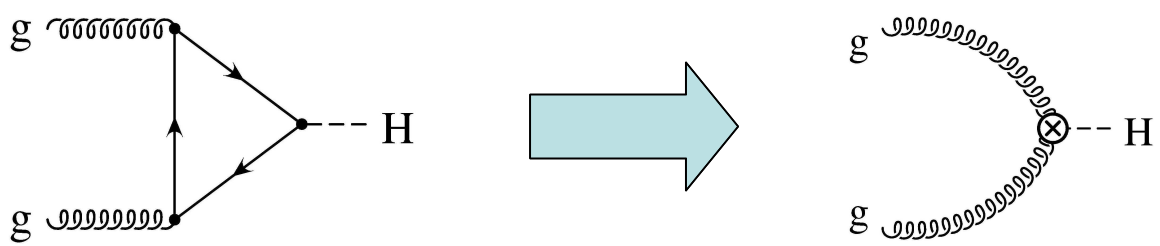
Rapid approach to heavy quark limit

Gluon Fusion

- Hadronic cross section

$$\sigma(s,M_H)=\Sigma_{ij}\int_0^1 dx_1\int_0^1 dx_2\, f_i(x_1,\mu_F)\, f_j(x_2,\mu_F)\int dx\,\delta\left(1-\frac{M_H^2}{x_1x_2s}\right)x\hat{\sigma}_{ij}$$

- QCD corrections
  - Dominated by heavy top loops
  - NLO cross section known for arbitrary top quark mass
  - NNLO cross section known only in $M_t \to \infty$ limit

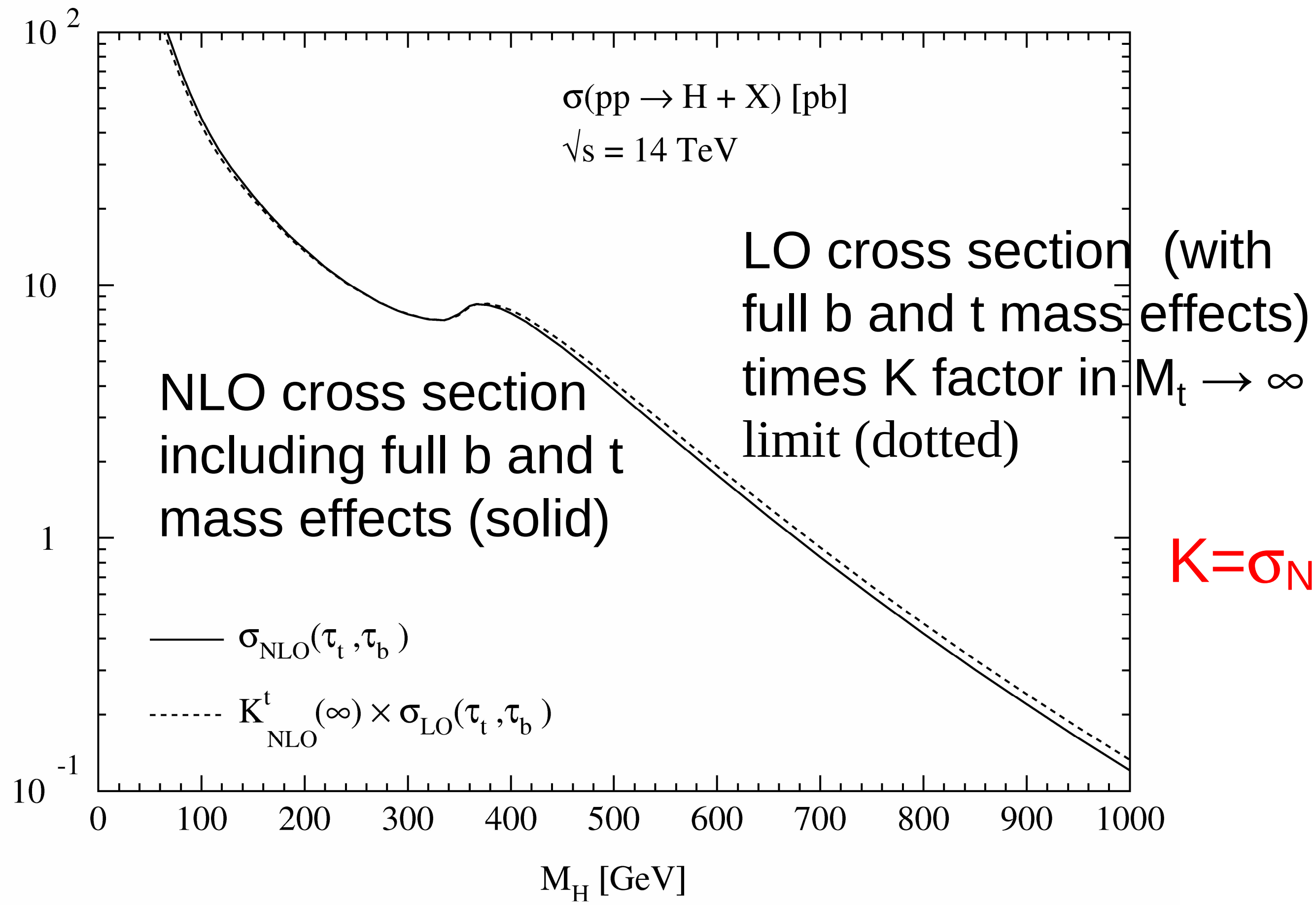


Overview

- NLO QCD corrections large (increase LO rate by 80-100%)
- NNLO corrections to σ increase rate by 15-20% for $M_H < 200$ GeV
- Soft gluon resummation increases rate by ~ 6%
- EW corrections increase rate by ~ 5%

Corrections all increase cross section

$M_t \rightarrow \infty$ Excellent Approximation for NLO $gg \rightarrow H$ rate



$K = \sigma_{NLO} / \sigma_{LO}$

Kraemer, Laenen, Spira, hep-ph/9611272

Effective Lagrangian Approach

- For heavy top, integrate out top

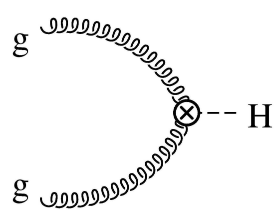
$$L = C_t(m_t,\mu)\frac{H}{v}\frac{\alpha_s(\mu)}{12\pi}G_{\mu\nu}{}^{A}G^{\mu\nu A}$$

- C_t known to NNLO

$$C_t(m_t,\mu) = 1 + \frac{\alpha_s(\mu)}{4\pi}(5C_A - 3C_F) + \left(\frac{\alpha_s(\mu)}{4\pi}\right)^2(.....)$$

Known

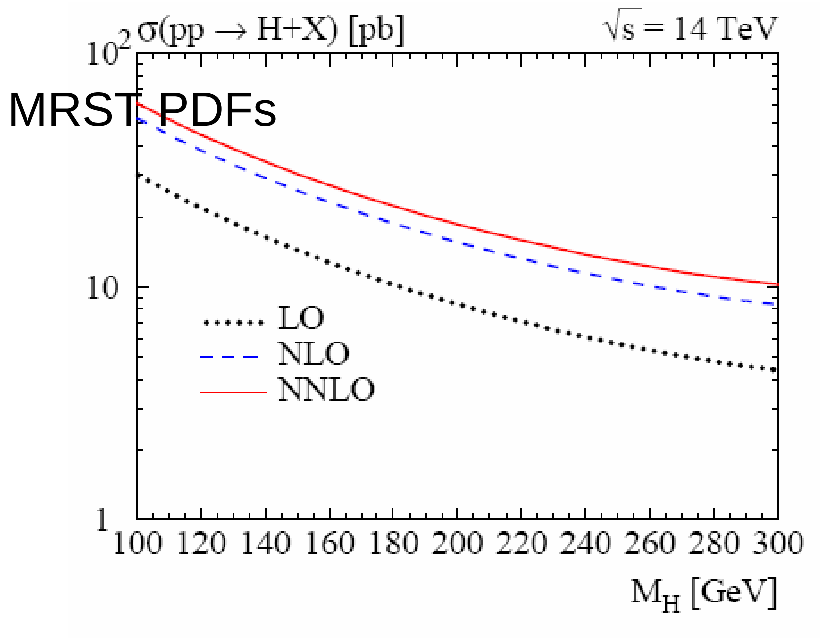
- Generates effective vertices



Kramer, Laenen, Spira, arXiv:hep-ph/9611272, Chetyrkin, Kniehl, Steinhasuser, arXiv:hep-ph/9705240

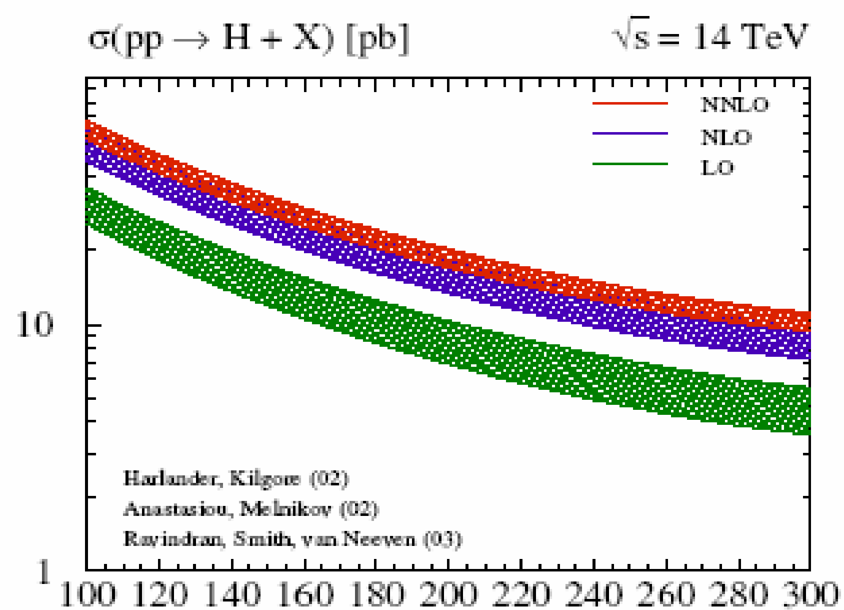
NNLO Result

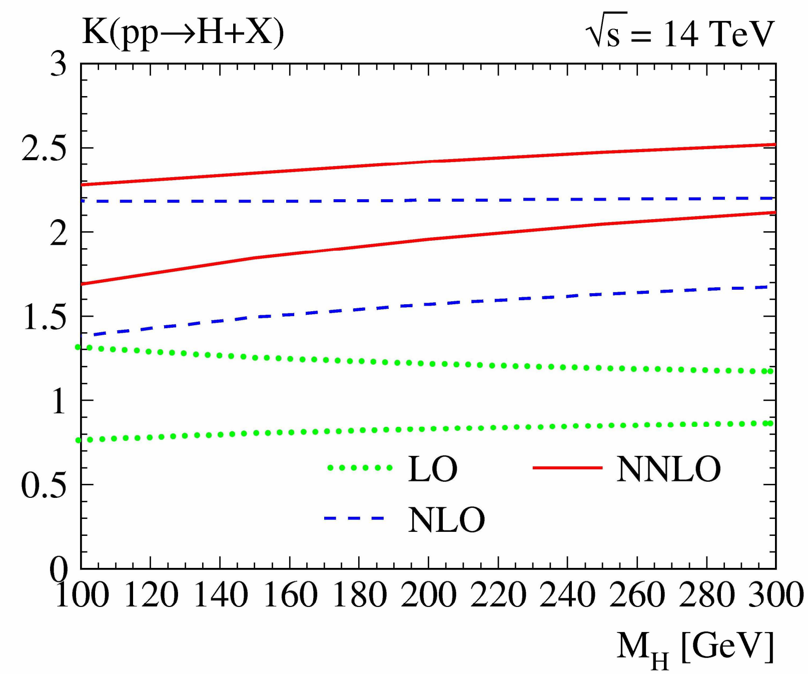
- Only in large M_t limit
  – Normalize to exact LO result



Harlander & Kilgore, hep-ph/0201206;Ravindran, Smith, & van Neerven, hep-ph/0409088; Anastasiou & Melnikov, arXiv:0207004

Scale Dependence Poor Estimate of Uncertainty

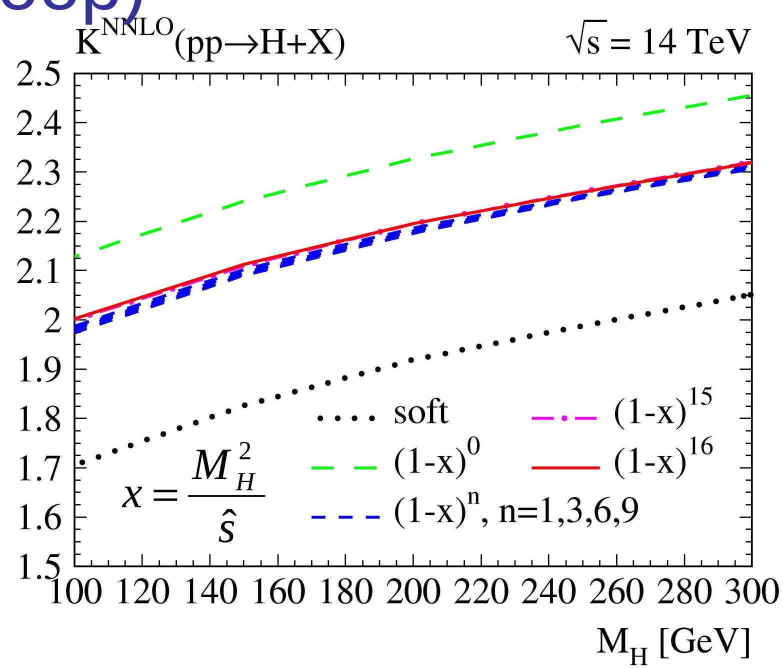


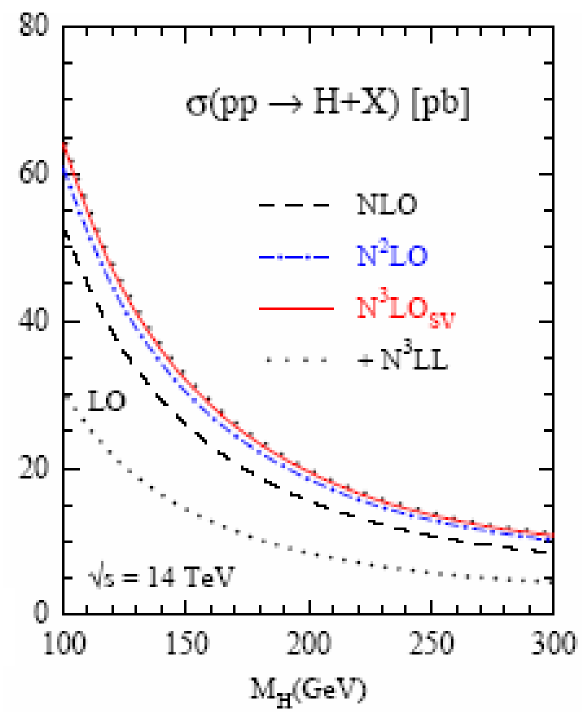


$M_H/2 < \mu_R, \mu_F < 2\, M_H$

Soft Contribution

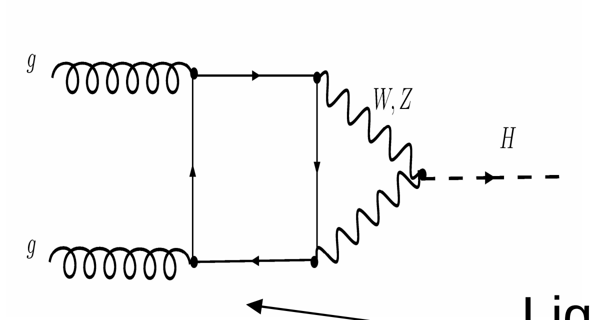
- Why should large M_t limit work?
- Much of the correction comes from soft contribution (which doesn't resolve top quark loop)





Kilgore and Harlander

Electroweak Contributions



Light Quarks

Enhanced by N_{lf}, No Yukawa suppression

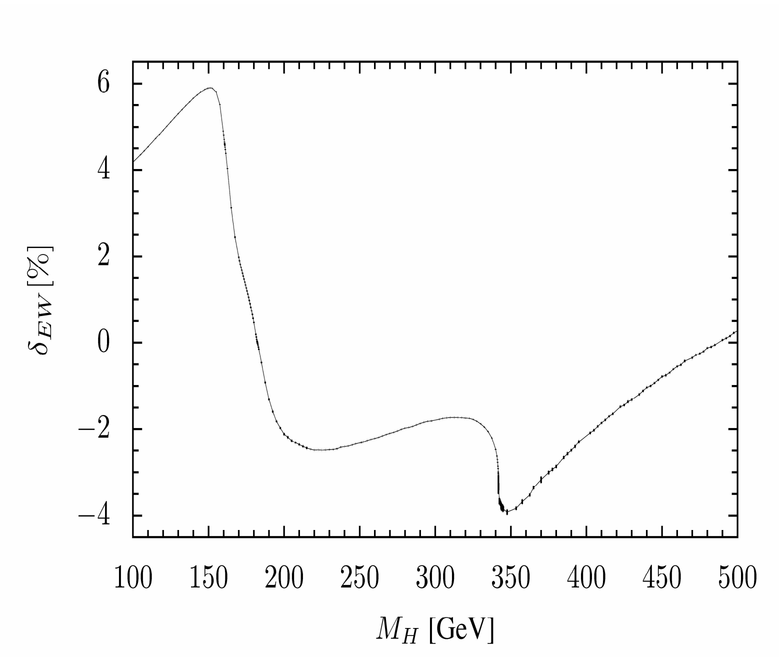
$$L_{eff} = \frac{\alpha_s}{12\pi} \frac{H}{v} C_1 G_{\mu\nu}{}^{A} G^{\mu\nu A}$$

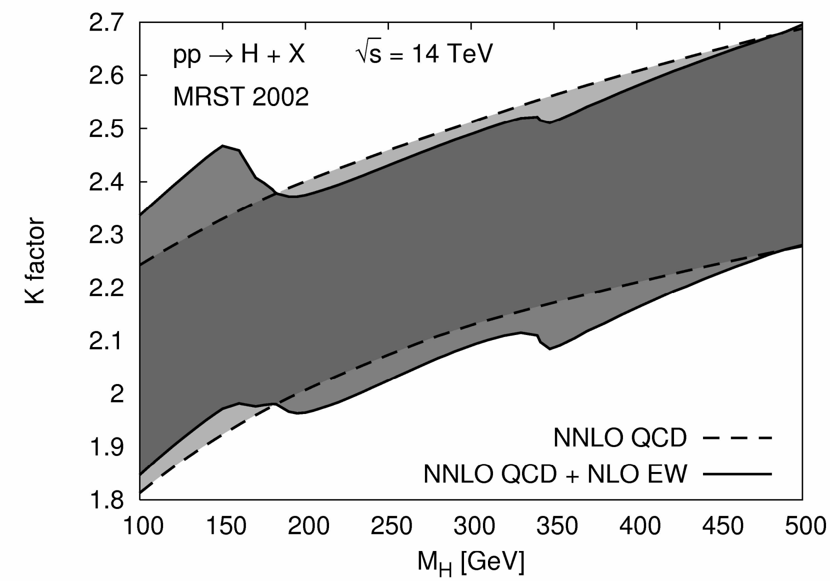
$$C_1 = 1 + \alpha_S C_a + \alpha_S{}^2 C_b + \delta_{EW}$$

$$\boxed{\delta_{EW} = \frac{3\alpha}{16\pi s_W^2} \left[\frac{2}{c_W^2} \left(\frac{5}{4} - \frac{7}{3} s_W^2 + \frac{22}{9} s_W^4 \right) + 4 \right]}$$

Aglietti, Bonciani, Degrass, Vicini, arXiv:0404071,
Actis, Passarino, Sturm, Uccirati, arXiv.0809.1301

Electroweak Contributions





Scale variation, $M_H/2 < \mu_R, \mu_F < 2\ M_H$

Actis, Passarino, Sturm, Uccirati, arXiv.0809.1301

Do EW/QCD Corrections Factorize?

- Can we write:

$$\boxed{C_1 = (1+\delta_{EW})(1+\alpha_S C_a + \alpha_S{}^2 C_b)} \quad ?$$

$$C_1 = 1 + \alpha_S C_a + \alpha_S{}^2 C_b + \delta_{EW}\left(1 + \alpha_S C_{a,EW} + \alpha_S{}^2 C_{b,EW}\right)$$

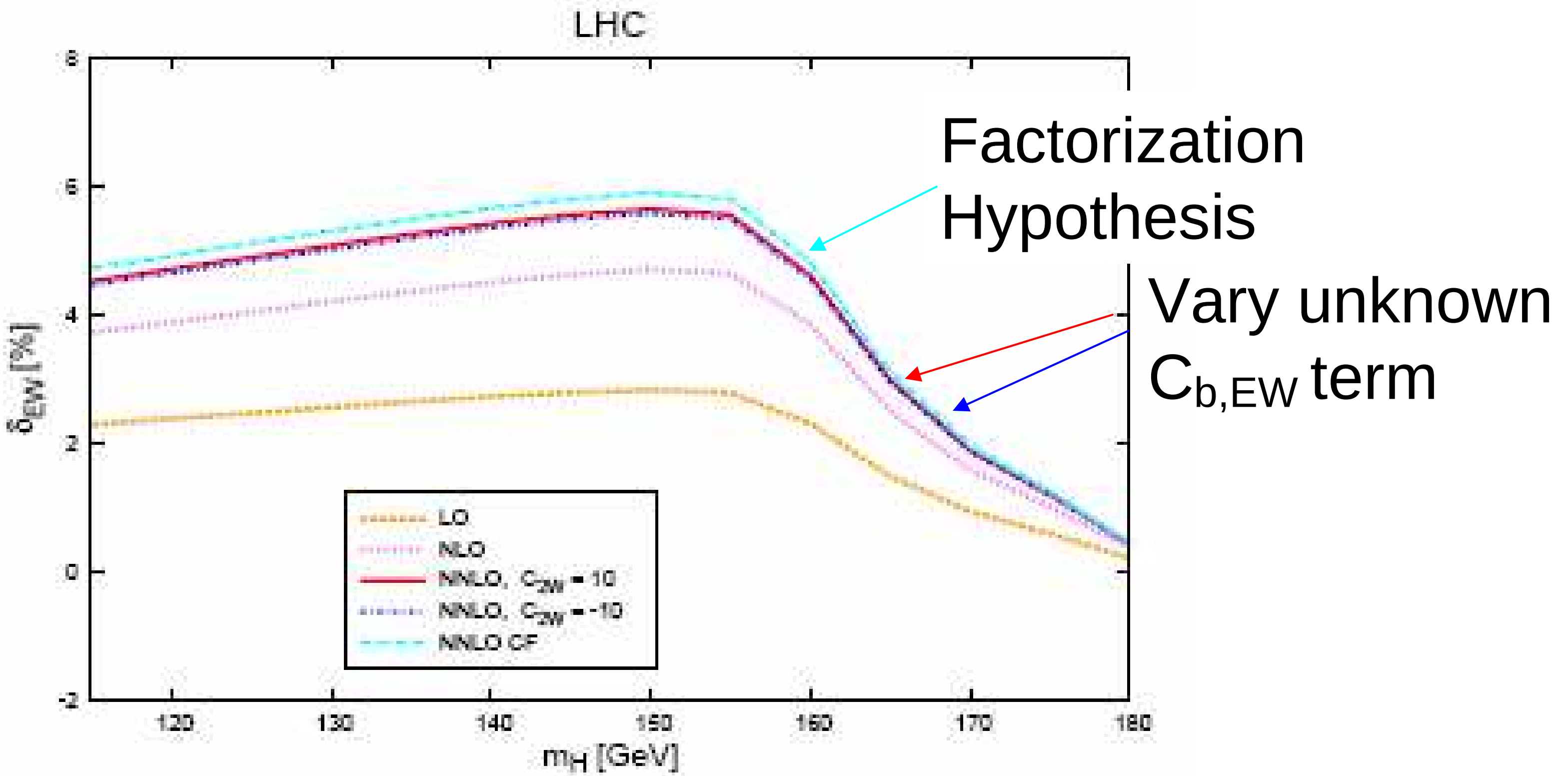
Unknown

Mixed QCD-EW Effects

- Do EW effects receive large QCD enhancements?
  - Exact calculation requires 3-loop diagrams with many mass scales
  - Compute $C_{a,EW}$ in limit $M_H/M_W \ll 1$
  - $C_{a,EW}$=7/6 (would be 11/4 if QCD-EW factorized)

Anastasiou, Boughezal, Petriello, arXiv:0811.3458

EW-QCD Factorization Good Approximation

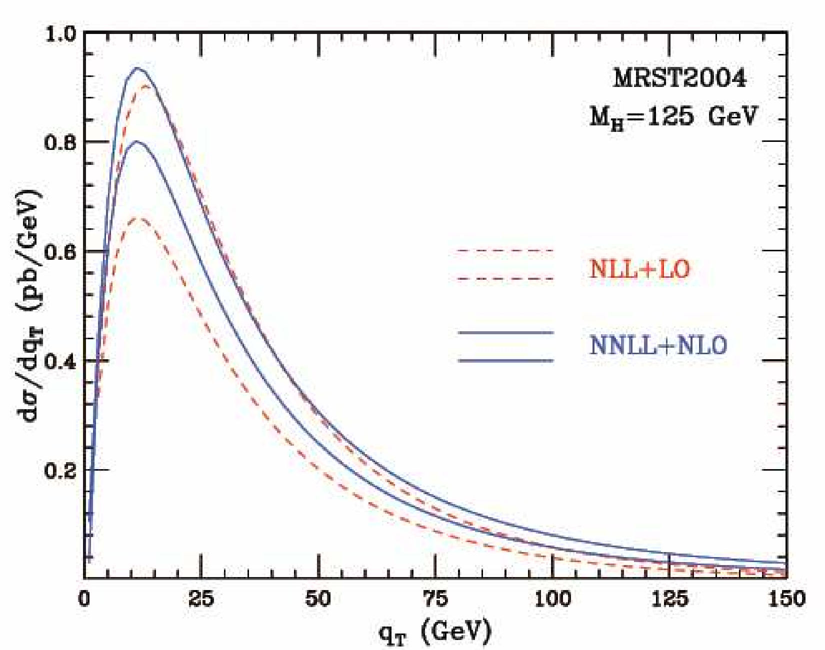


Factorization approximation works well

q_T distribution of Higgs

- Gluon fusion produces Higgs with no q_T at LO
- Non-zero q_T first at $O(\alpha_S^3)$ from $gg \to Hg$
- Large M_t valid for $q_T < M_H$, M_t
- NLO QCD known in large M_t for $gg \to Hg$

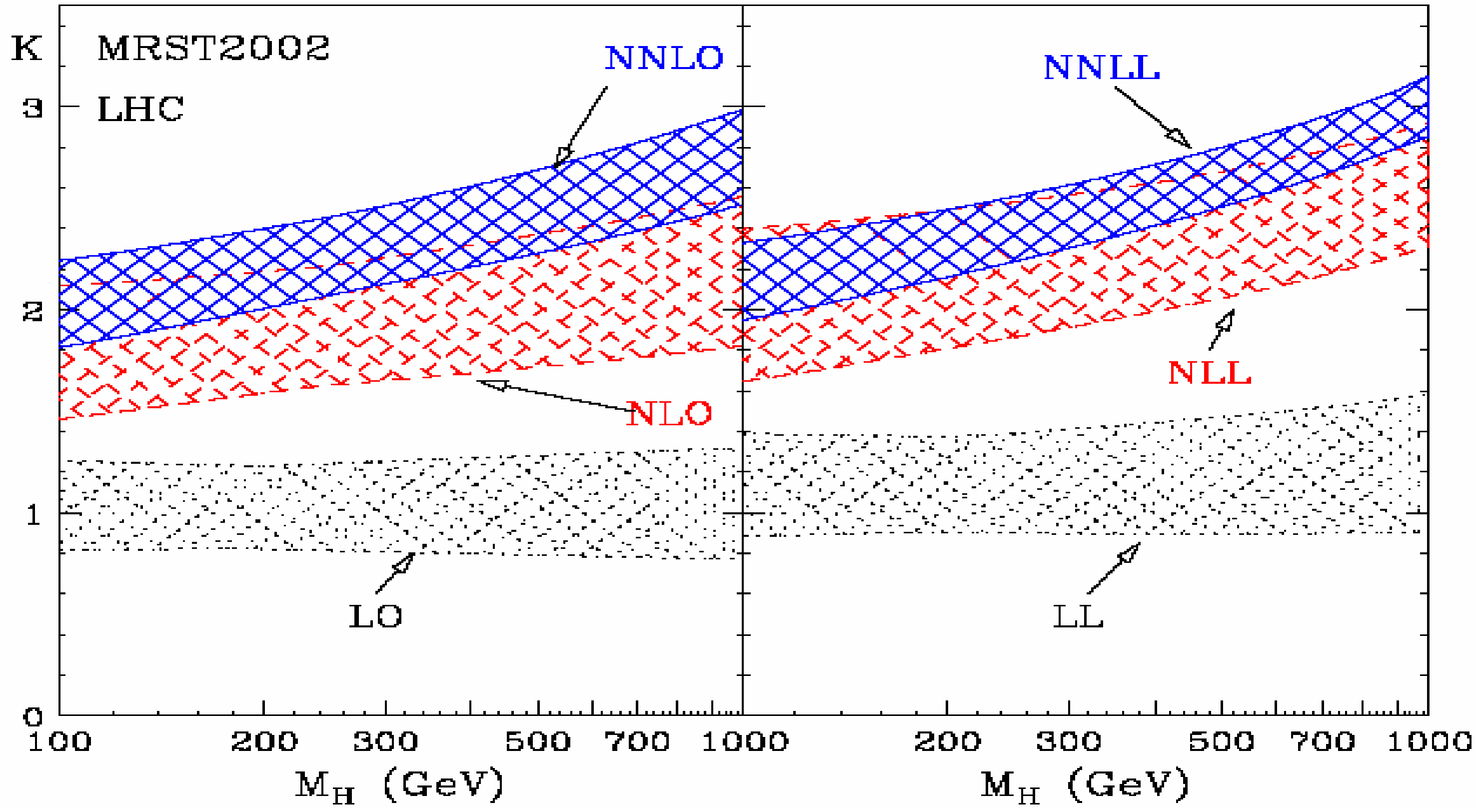
Re-Sum Soft Gluons



- Large q_T, fixed order calculation valid
- Most events at small q_T where large logs, $\alpha_S^n \ln^{2n} M_H^2/q_T^2$, must be resummed to all orders
- Resummed calculation at low q_T matched to fixed order at large q_T

Bozzi, Catani, deFlorian, Grazzin, 2003, hep-ph/0508068, arXiv:0707.3887

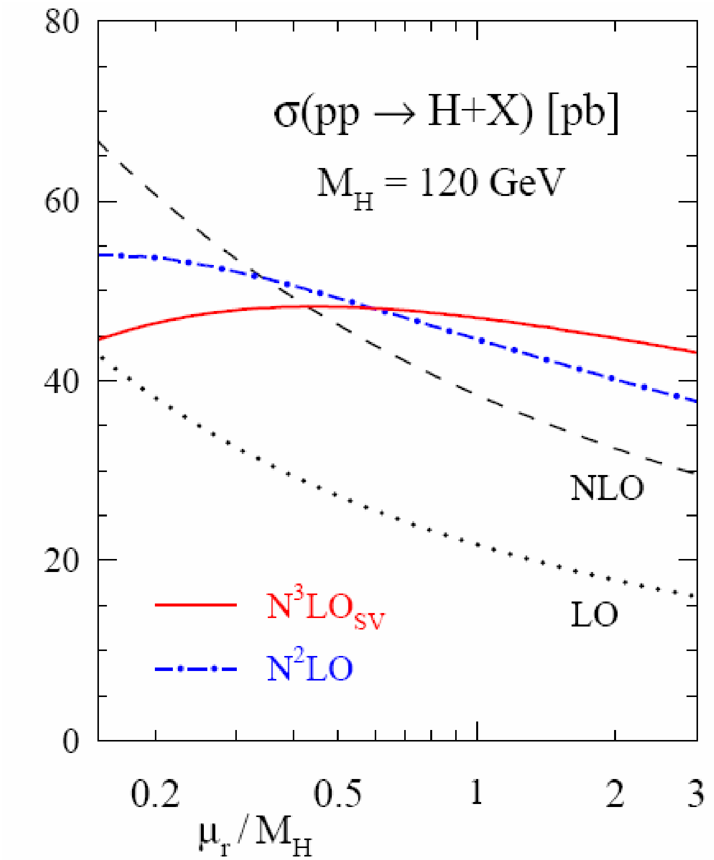
Soft Resummation



Catani, Grazzini, de Florian, Nason, 2003

N^3LO Soft Terms

- Improves scale dependence



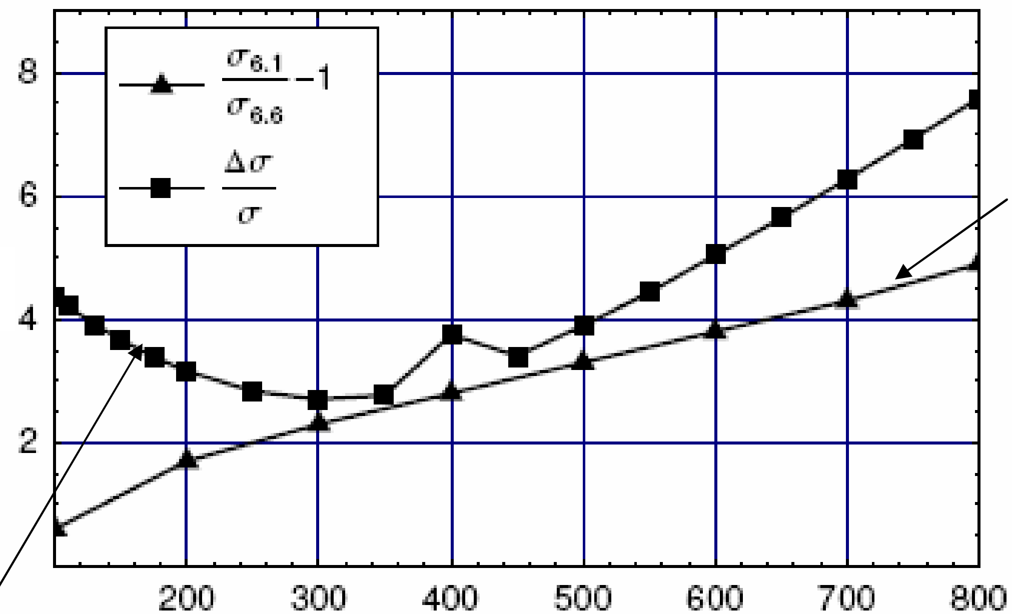
Moch, Vogt; Laenen, Magnea (2005)

PDF Uncertainties in $gg \rightarrow H$

NLO cross section with $\mu_R = \mu_F = M_H$

Uncertainty relative to previous CTEQ parameterization (CTEQ6.1)

%



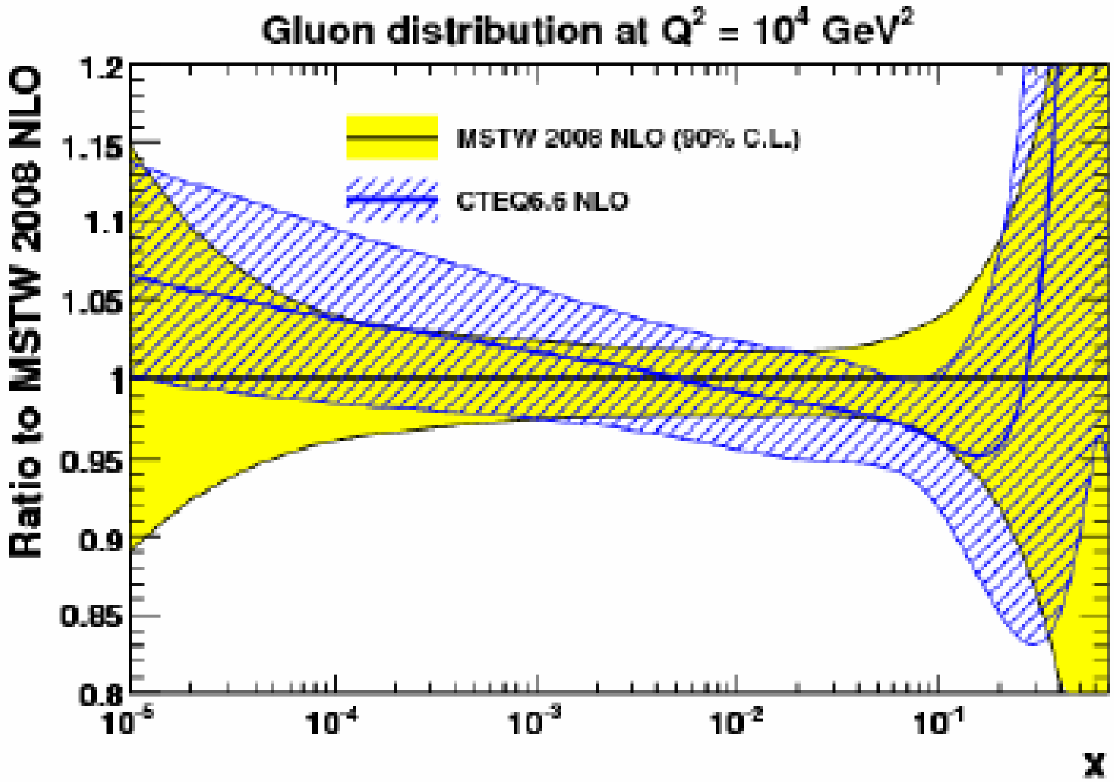
M_H (GeV)

PDF uncertainty of CTEQ6M fit

Hsieh & Yuan, ArXiv:0806.2608

New PDFS

- MSTW2008



Beyond Large M_t

- Compute large $\hat{s}$ limit for gg$\rightarrow$H
- Use NLO as testing ground
- Idea:
  – High energy behavior is different for pointlike ggH effective vertex and true vertex with resolved top

$$\hat{\sigma}_{gg} \approx \hat{\sigma}_{LO}\left(\delta(1-x) + \frac{\alpha_S}{\pi} B(x, M_t)\right) \qquad x = \frac{M_H^2}{\hat{s}}$$

$$\left.\begin{aligned} B(x,\infty) &\approx \ln(x) \\ B(x,M_t) &\approx \text{constant} \end{aligned}\right\} \text{High energy limits}$$

  – Construct interpolating function

Marzani, Ball, DelDuca, Forte, Vicini, arXiv:0801.2544

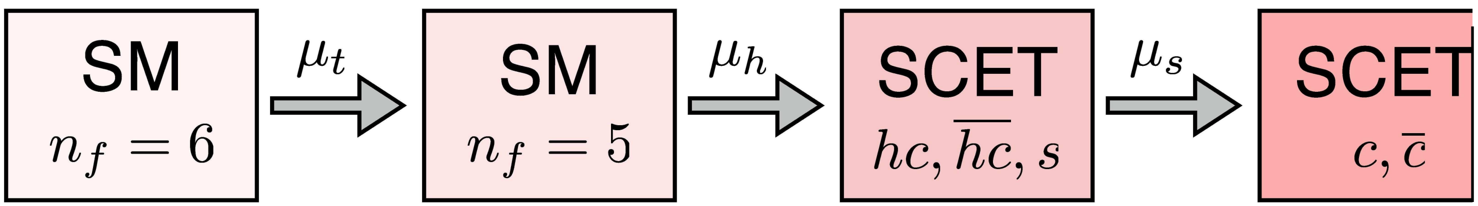
Beyond the Large M_t Limit

	K_{NLO}	K_{NNLO}
	M_H=130 GeV	
Large M_t	1.800	2.140
Exact	1.797	
Approx.	1.796	2.136
	M_H=280 GeV	
Large M_t	1.976	2.420
Exact	1.958	
Approx.	1.959	2.394

Marzani et al, arXiv: 0809.4934

Sum π^2 and Soft Logs

- Series of effective field theories



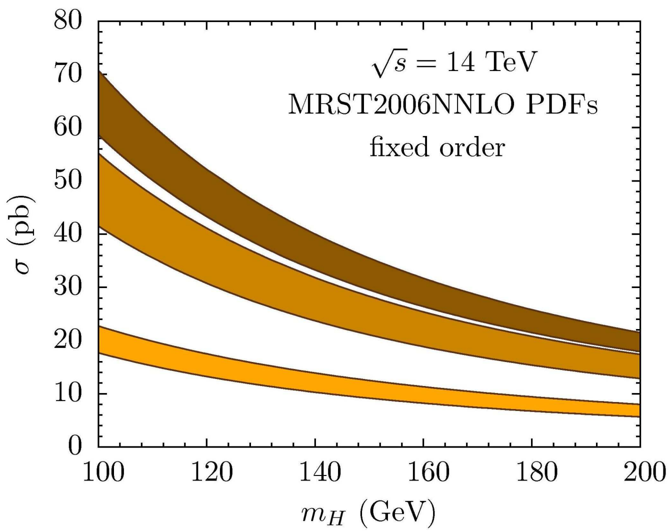
$C_t(m_t^2, \mu_t^2)$ $\quad$ $H(m_H^2, \mu_h^2)$ $\quad$ $S(\hat{s}(1-z), \mu_s^2)$

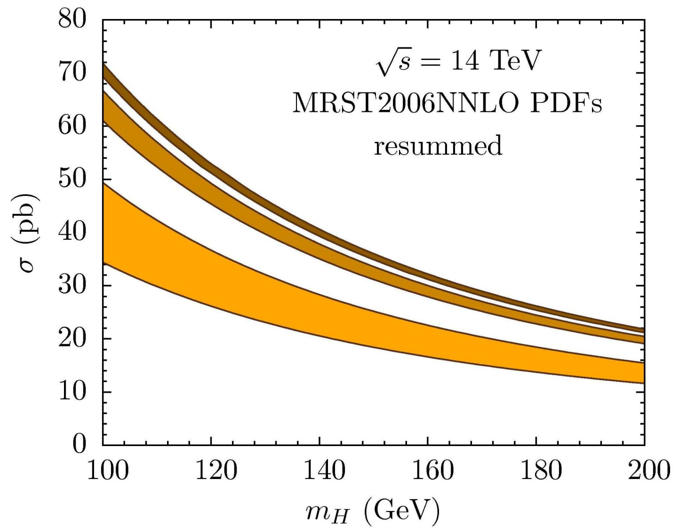
Integrate out top quark

Integrate out hard gluons

Use Renormalization Group

- Sum terms $(C_A \pi \alpha_s)^n$



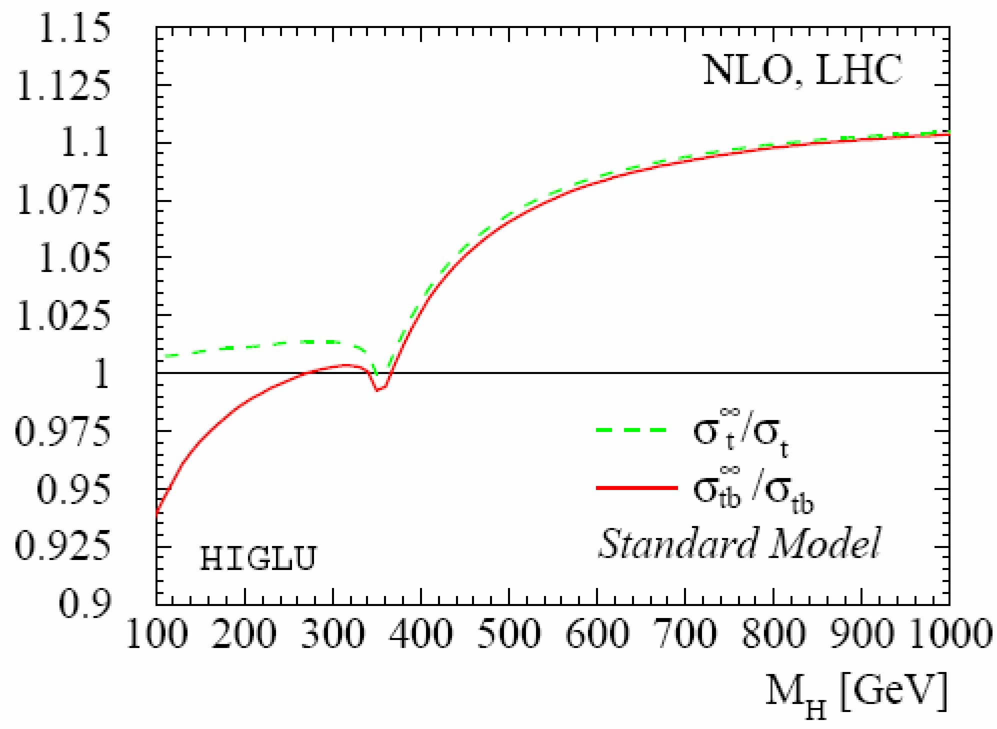


- Resummed > fixed order by 8% (M_H=120 GeV)
- Note: Same PDFs used for all curves

Ahrens, Becher, Neubert, Yang, arXiv:hep-ph/0808.3008, 0809.4283

b Contribution to NLO

- b-loops receive smaller QCD NLO contribution than top loops in gluon fusion for $M_H < 2\ M_t$



Harlander

How big are the uncertainties?

- Goal: put it all together
- MRST2006 NNLO PDFs
- Top contribution to NNLL+NNLO in large M_t limit (normalized to exact LO)
- Bottom and b-t loops at NLO with exact mass dependence
- EW corrections assuming factorization

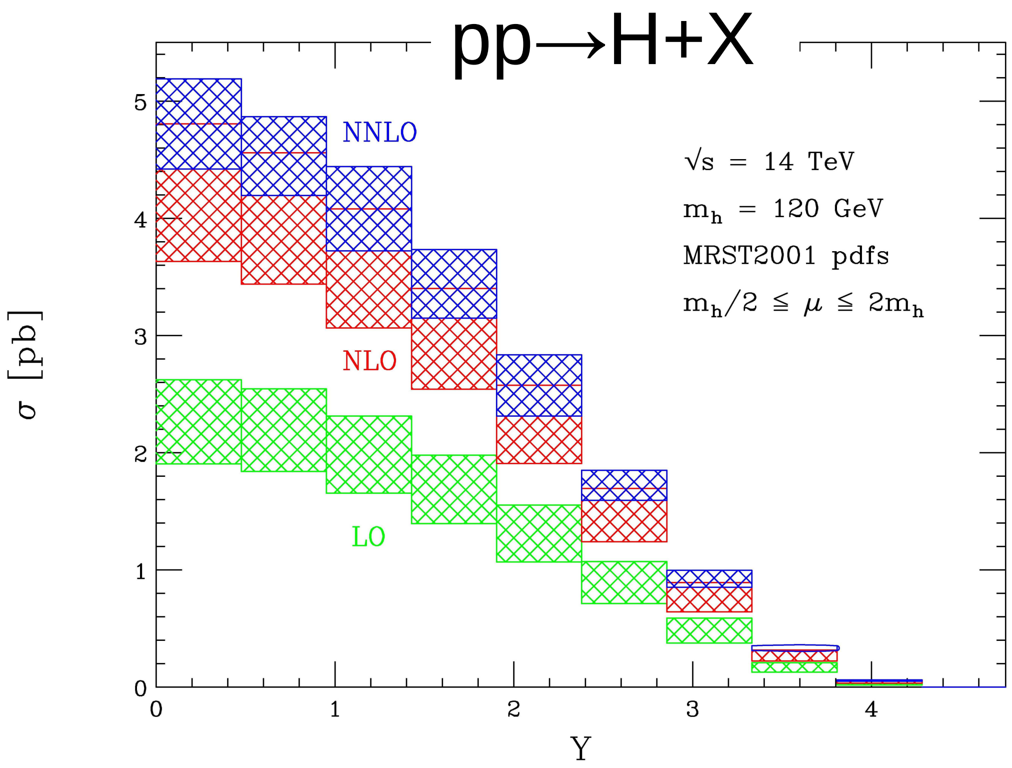
Best Estimates

- Grazzini (Zurich)
  - wrt previous results, +30% for M_H=115 Gev, +6% for M_H=300 GeV
  - MRST2008 PDFs have small effect at LHC

M_H	$\sigma_{NNLL+NNLO}$ (pb)	Scale	PDF
120	54.52	+5.13, -5.35	+.91, -.96
130	47.53	+4.33, -4.53	+.76, -.81
150	37.11	+3.18, -3.36	+.53, -.58

Scale uncertainty ≈ 10%

Beyond Total Cross Sections



Estimates of scale dependence inadequate

Higher order corrections change shapes

Anastasiou, Dixon, & Melnikov, hep-ph/0211141, hep-ph/0501130

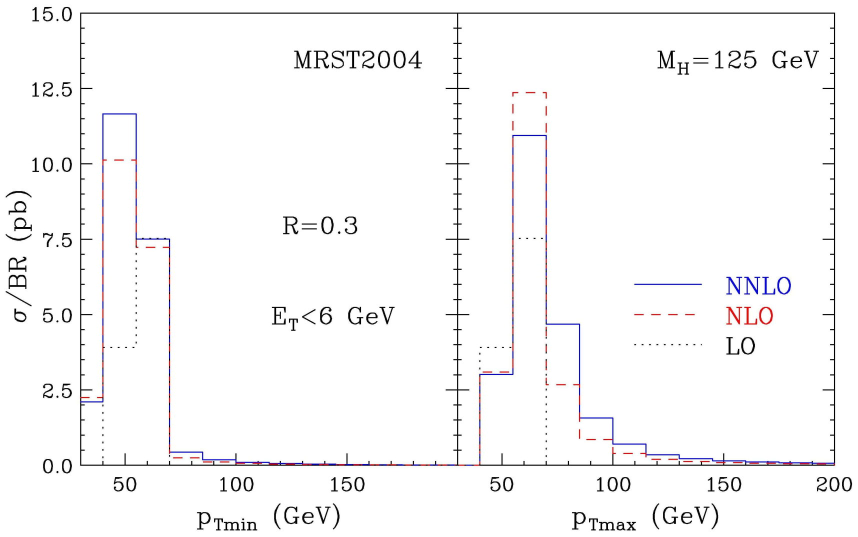
Distributions to NNLO

- Do cuts change effects of higher order QCD?
  - Effects of higher order QCD reduced with jet veto
- HNNLO, FEHIP: NNLO MCs
  - NNLO with experimental cuts for $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$, $H \to ZZ$

NNLO Monte Carlos

NNLO MC for gg→H→γγ

LHC



Photons isolated: Total energy in cone of ΔR=.3 less than 6 GeV

Note impact of NNLO corrections

Catani & Grazzini, hep-ph/0703012

Anastasiou, Melnikov, & Petriello, hep-ph/0501130

NNLO, H→γγ with cuts

- gg→H → γ γ

m_h	$\sigma^{\text{cut}}_{\text{NNLO}}/\sigma^{\text{inc}}_{\text{NNLO}}$	$K^{(2)}_{\text{cut}}/K^{(2)}_{\text{inc}}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

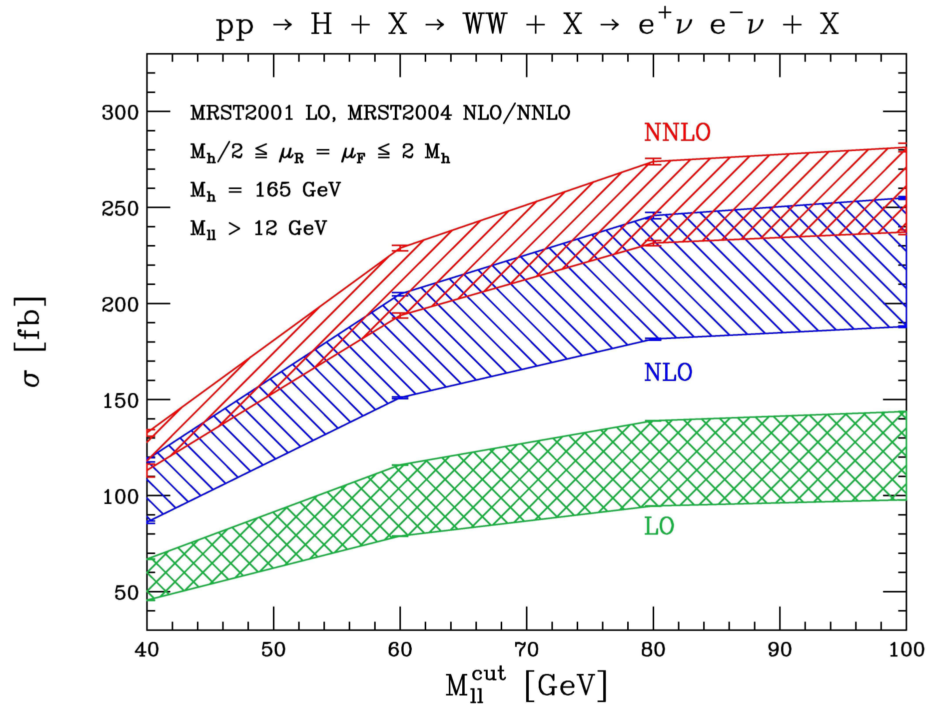
Anastasiou, Melnikov, Petriello, 2005

$H \to W^+W^- \to l\nu l\nu$ @ NNLO

- Example: M_H=165 GeV
- No cuts, K_{NLO}=1.84, K_{NNLO}=2.21 ($\mu=M_H$)
- Simple pre-selection cuts, K_{NLO}=1.83, K_{NNLO}=2.19
  - $p_{Tl} > 20$ GeV, $|y| < 2$, $p_{Tmiss} > 20$ GeV, $M_{ll} < 80$ GeV, $\Delta\varphi_{ll} < 135°$
- Selection cuts significantly reduce size of higher order contributions, K_{NLO}=1.19, K_{NNLO}=1.11
  - $p_{Tmin,l} > 25$ GeV, 35 GeV $< p_{Tmax,l} <$ 50 GeV, $M_{ll} <$ 35 GeV, $\Delta\varphi_{ll} < 45°$, no jets with $p_T > p_{Tveto}$

Grazzini, arXiv:0801.3232, Anastasiou, Dissertori, Stockli, arXiv:0707.2373, Anastasiou, Dissertori, Stockli, Webber, arXiv:0801.2682

H→W⁺W⁻→lνlν @ NNLO



Band is wider at NLO than LO!

Grazzini, arXiv:0801.3232, Anastasiou, Dissertori, Stockl, arXiv:0707.2373

gg → H→ZZ →4l @ NNLO

- QCD corrections tend to make distributions harder

Cuts:

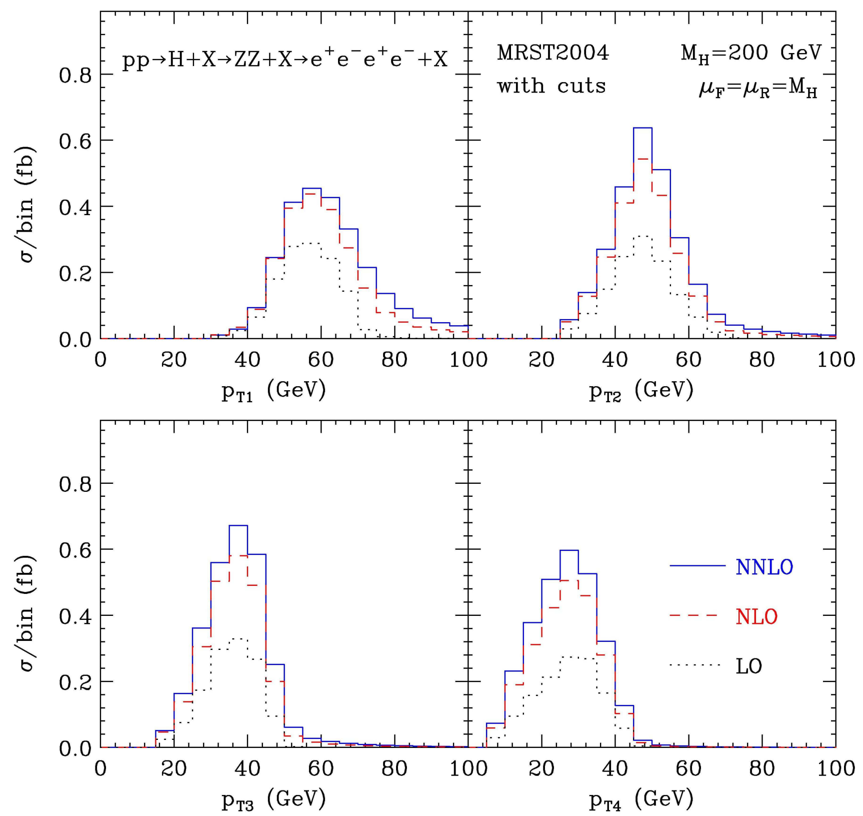
$p_{T1} > 30$ GeV, $p_{T2} > 25$ GeV,

$p_{T3} > 15$ GeV, $p_{T4} > 7$ GeV ,

$|y_l|<2.5$, leptons isolated,

81 GeV < m_{ll1} < 101 GeV,

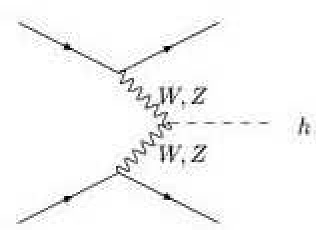
40 GeV < m_{ll2} < 110 GeV



Grazzini, arXiv:0801.3232

Vector Boson Fusion

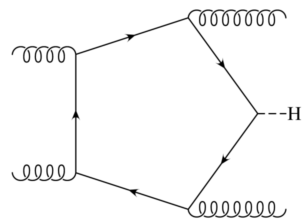
- QCD NLO corrections increase LO rate by 5-10%
  - Available in VBNLO program
- Implemented for distributions
  - Many of the backgrounds also known at NLO (Zeppenfeld et al)
- Important channel for extracting couplings

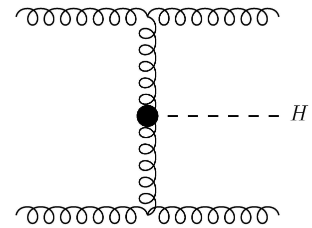


Zeppenfeld et al, 0811.4559

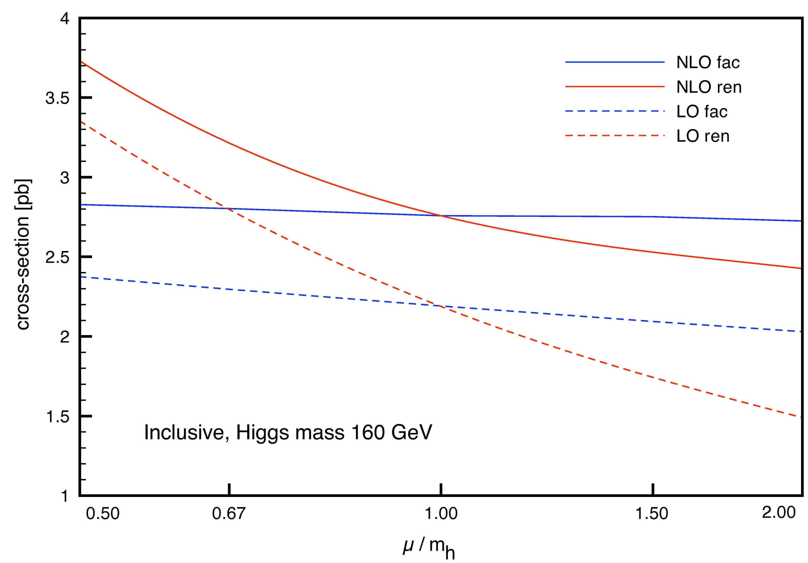
$gg \rightarrow ggH$

- Large contributions from $gg \rightarrow ggH$
  - Known exactly at one-loop
  - NLO known in large M_t limit
  - Renormalization scale dependence at NLO larger than expected (~ 35%)





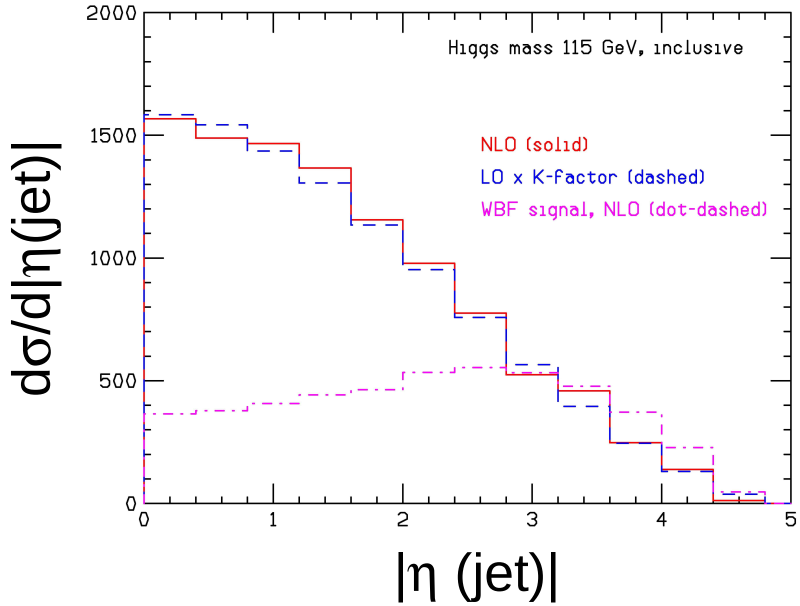
M_H (GeV)	115	160
σ_{LO} (fb)	271	172
σ_{NLO} (fb)	346	236
σ_{VBF} (fb)	911	731



Campbell, Ellis, Zanderighi, arXiv:0608194, Del Duca, Kilgore, Oleari, Schmidt, & Zeppenfeld, arXiv:0108030

gg→ggH

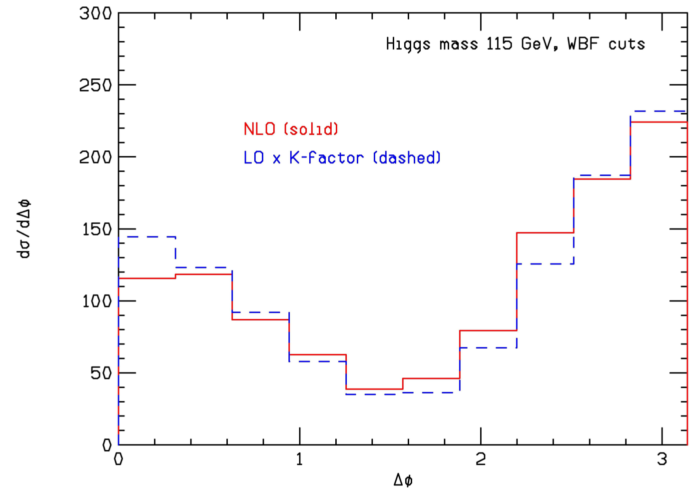
- NLO effects can be included with K-factor
- Inclusive cuts:
  - p_{Tjet}>40 GeV, $|\eta_{jet}|$<4.5, $R_{jet,jet}$>0.8
- gg cross section much larger than VBF rate



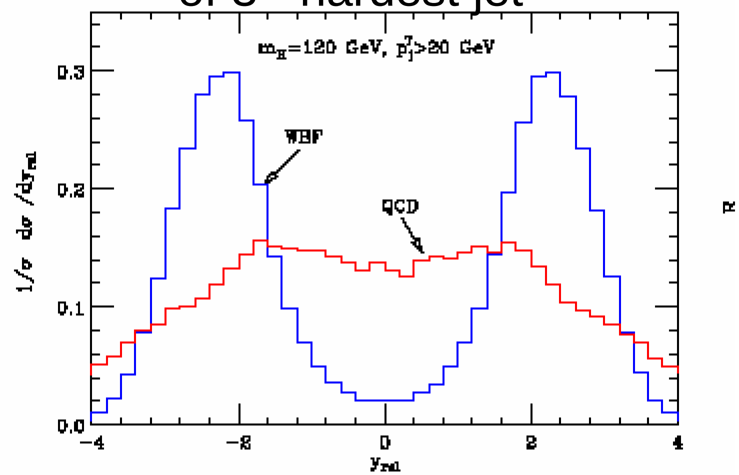
M_H (GeV)	115	160
σ_{LO} (pb)	3.50	2.19
σ_{NLO} (pb)	4.03	2.76
σ_{VBF} (pb)	1.77	1.32

Vector Boson Fusion

- Cuts effective at separating VBF signal from gg→ggh
  - Require tagging jets well separated in rapidity and in opposite hemispheres



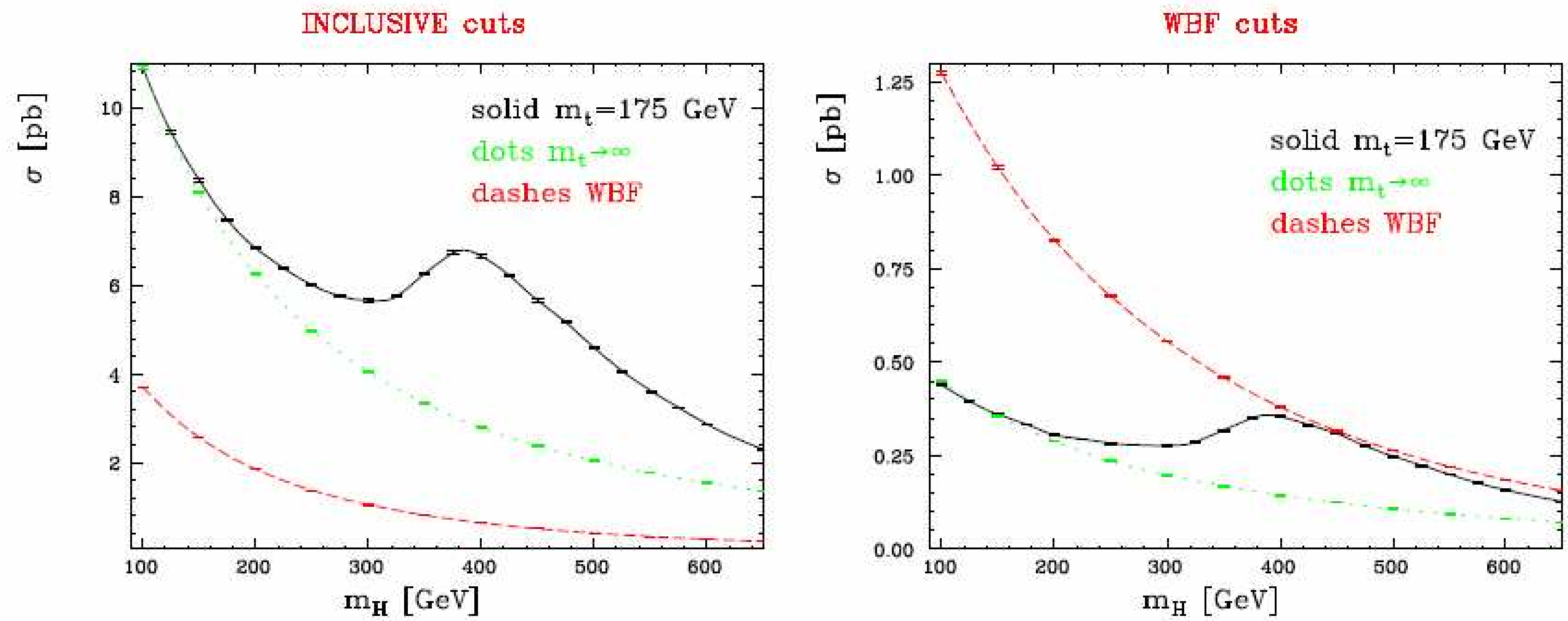
Azimuthal distribution of 3rd hardest jet



Campbell, Ellis, Zanderighi, arXiv:0608194,
Del Duca, Frizzo, Maltoni, JHEP05 (2004) 064

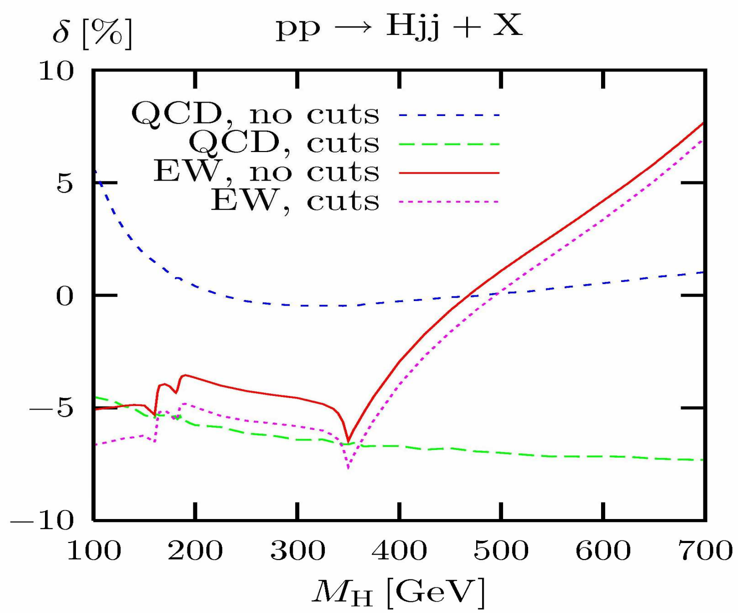
gg→ggH vs VBF

- Fourth generation would enhance ggH pollution



Zeppenfeld

QCD & EW Corrections to VBF

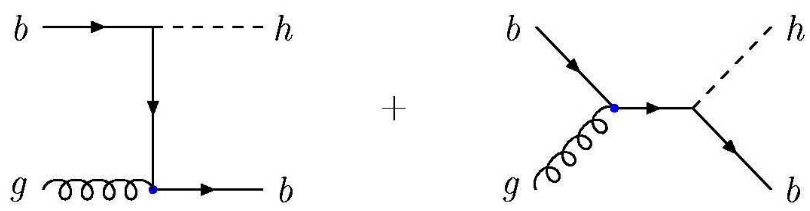


- EW corrections same size as QCD
- Cancellations for small M_H
- Cuts suppress cancellations

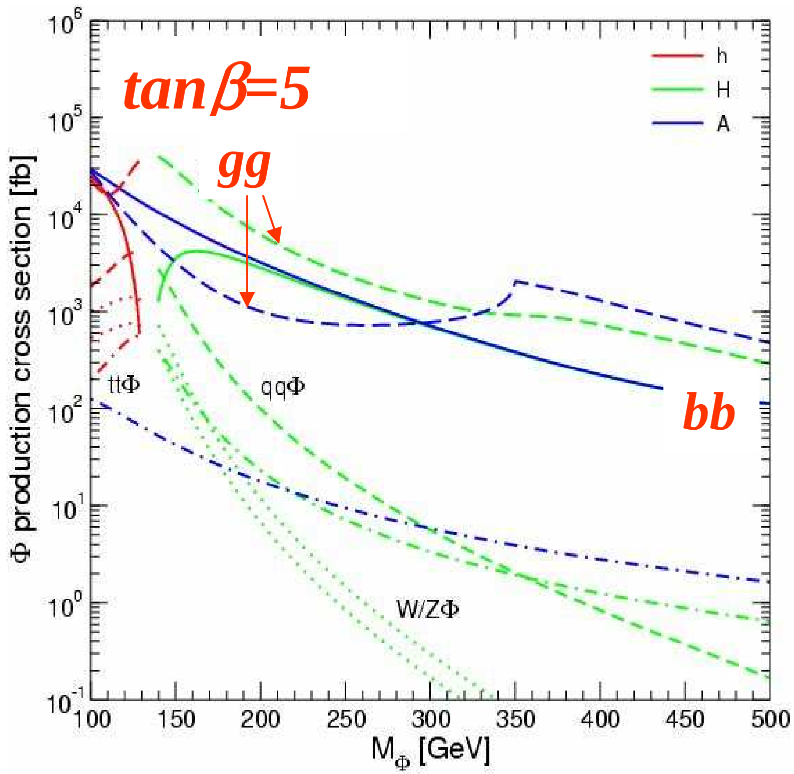
Ciccolini, Denner, Dittmaier, arXiv:0710.4749

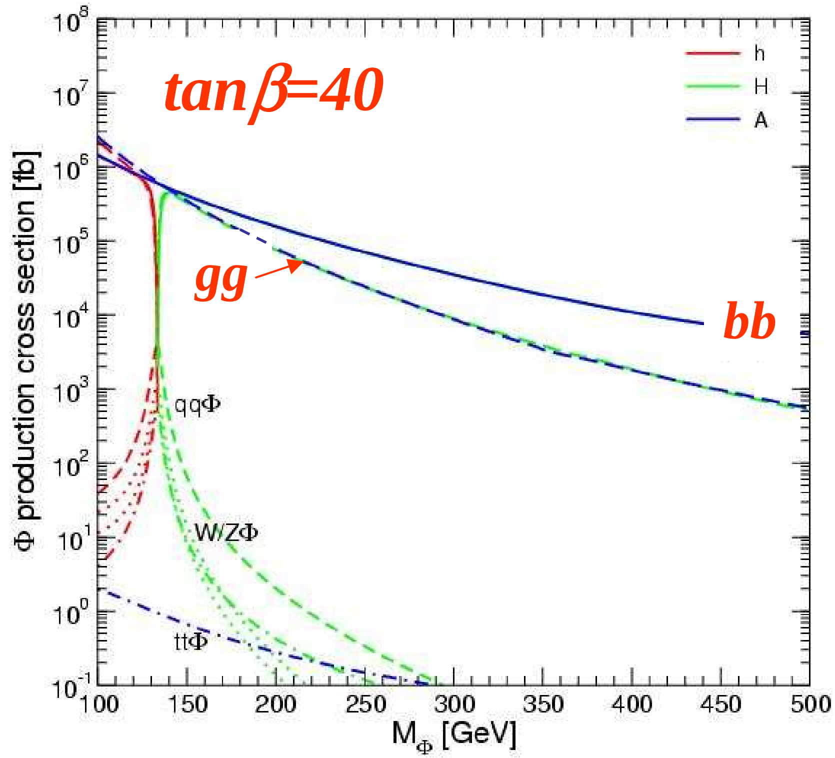
Beyond the SM

- MSSM is good test case
- New production mechanisms
- SUSY discovered with b's in much of parameter space



SUSY Higgs Rates at the LHC

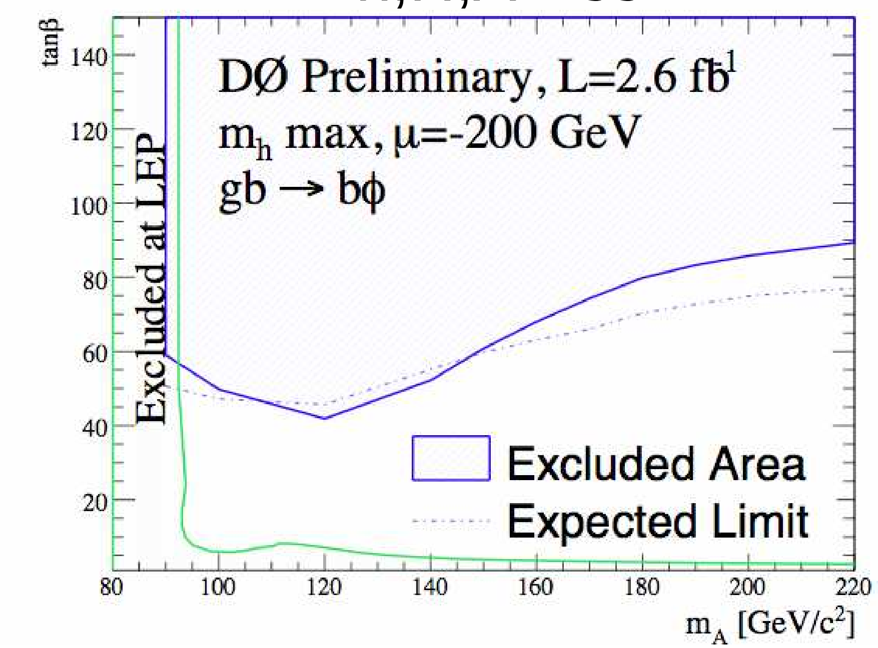


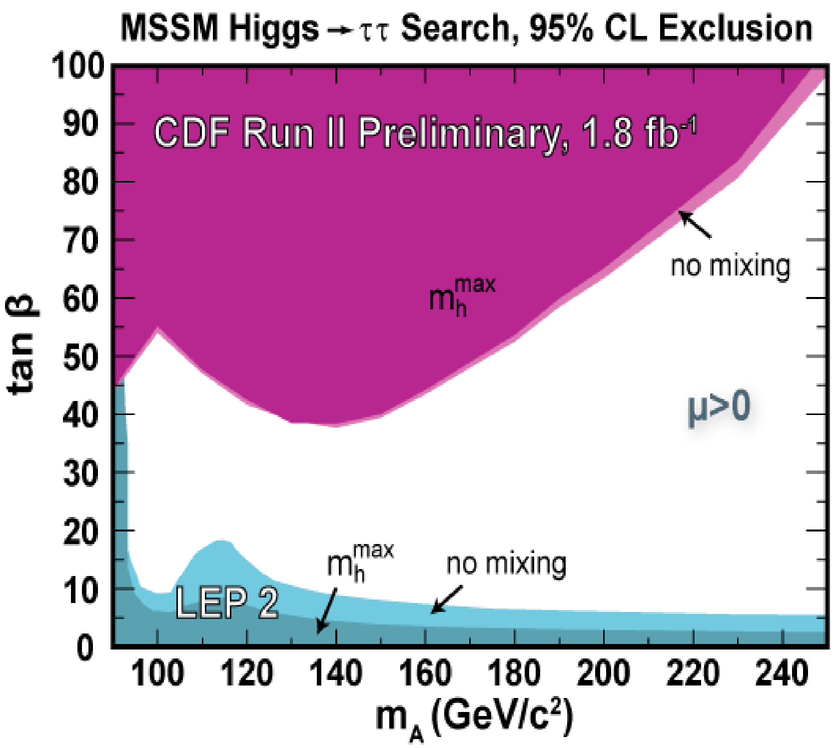


TeV4LHC Report

New Higgs Discovery Channels

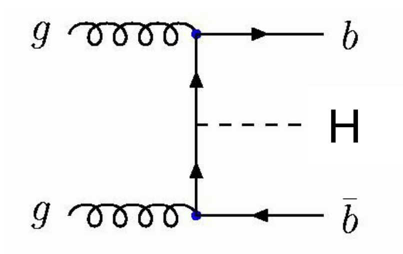
$h,H,A \rightarrow bb$



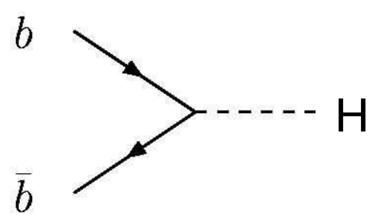


Two Schemes for PDFs:

- 4 flavor number scheme
  - No b quarks in initial state
  - Lowest order process involving Higgs and b's is $gg \to b\bar{b}H$
- 5 flavor number scheme
  - Define b quark PDFs (absorbs large logarithms)
  - Higgs produced with no p_T at lowest order ($b\bar{b} \to H$)
  - Higgs p_T generated at higher orders in expansion

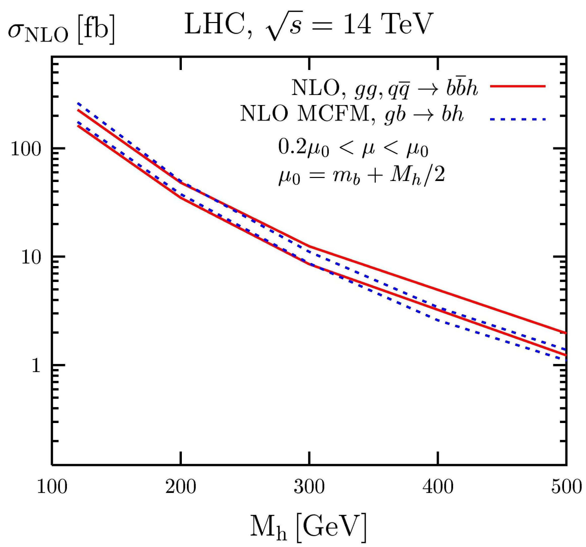


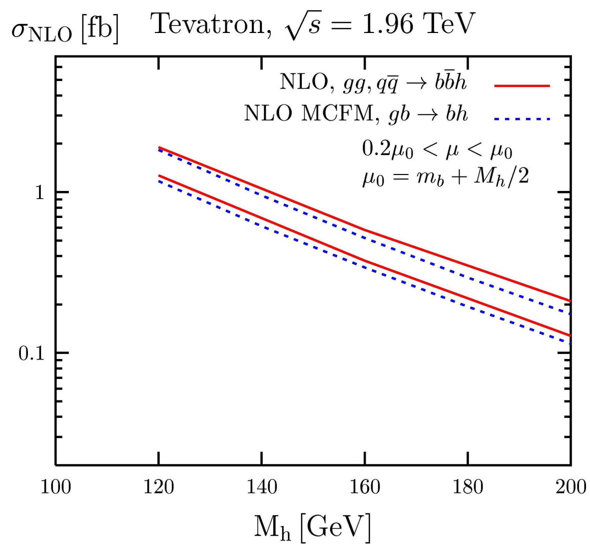
VS



pp→ b$\bar{\text{b}}$h: 1 b tag

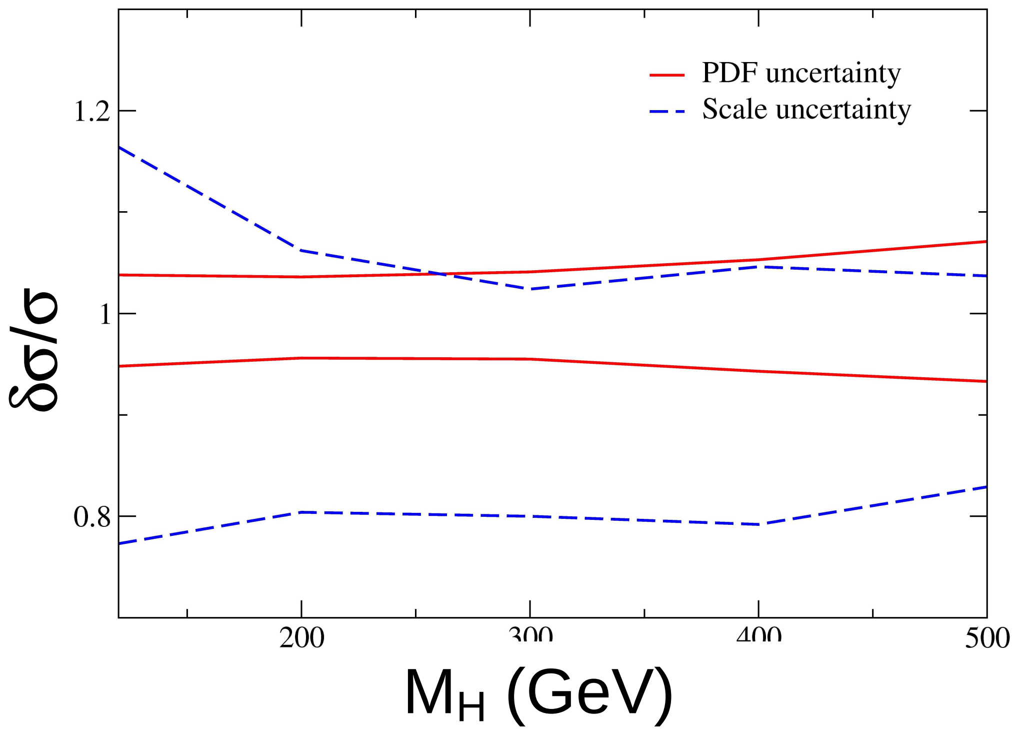
- Compare *5 flavor number scheme* (b PDFs) with *4 flavor number scheme* (no b PDFs) for total rates
- Consistent results in two schemes





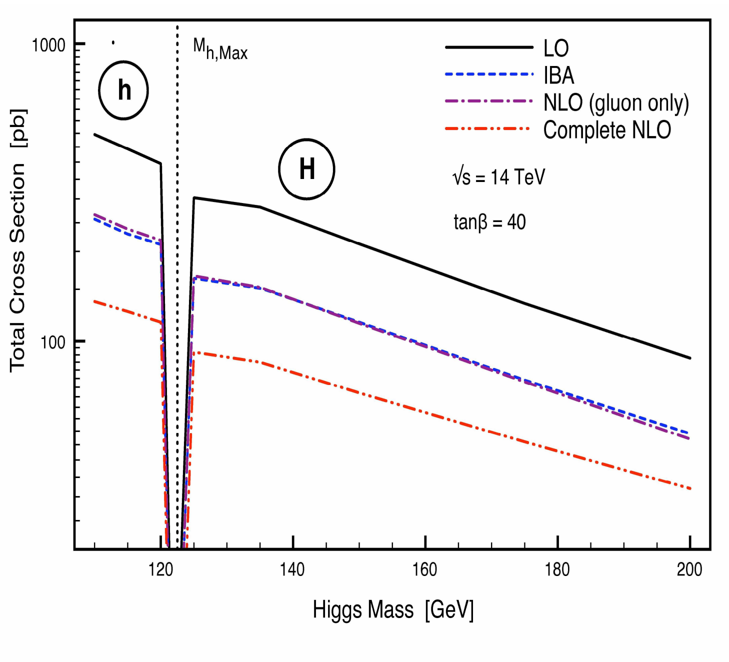
PDF/Scale Uncertainties

- bg→bH @ LHC (SM)

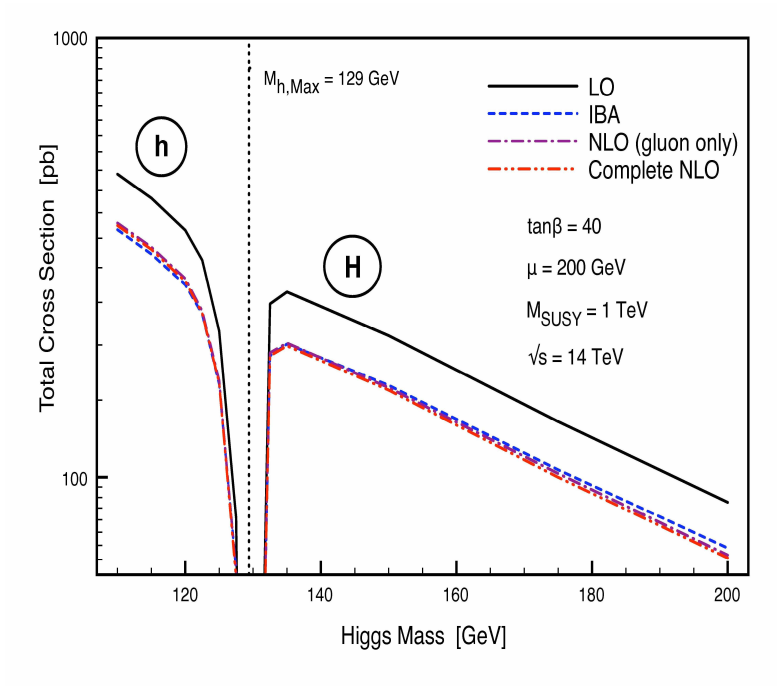


Dawson, Jackson, Reina, Wackeroth, hep-ph/0508293

SQCD Contributions



$m_{\tilde{g}}=m_{\tilde{b}}=250$ GeV



$m_{\tilde{g}}=m_{\tilde{b}}=1$ TeV

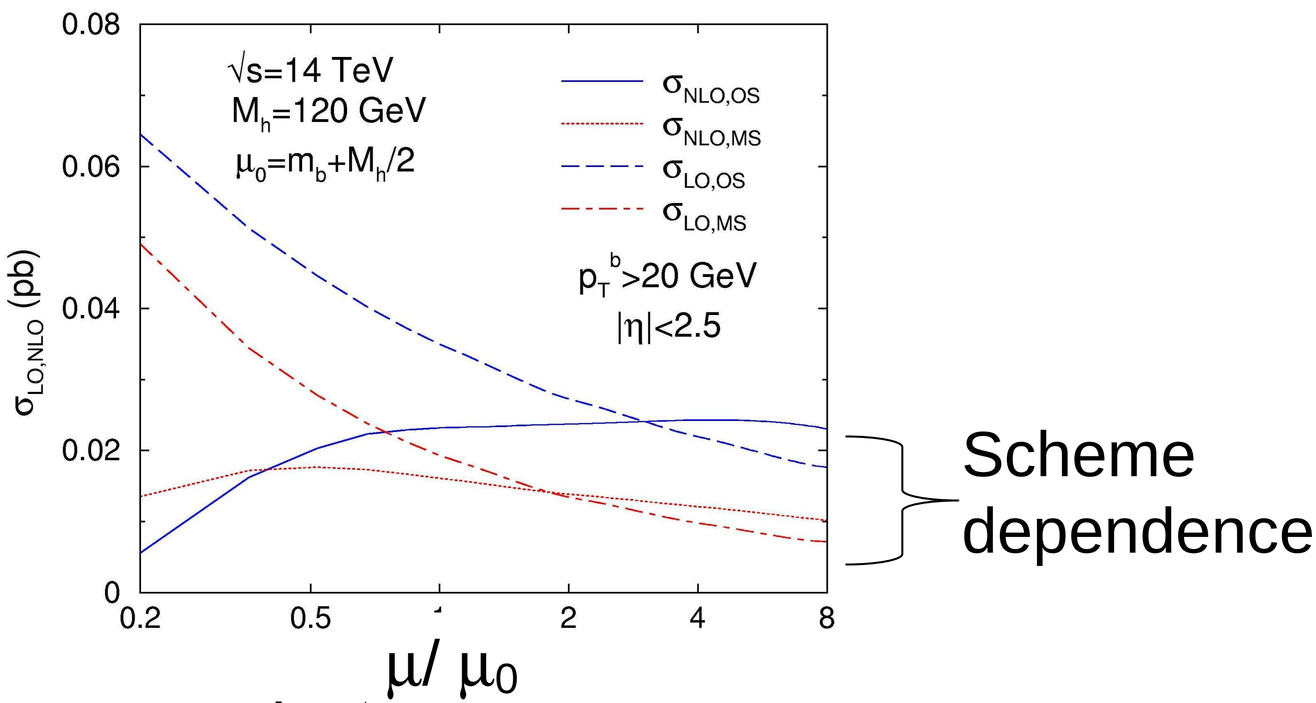
Squark and gluino loops relevant for moderate masses, effects decouple for large gluino mass

Dawson & Jackson, arXiv:0709.4519, Muhlleitner, Rzehak, Spira, arXiv:0812.3815

Scheme Dependence at NLO

•NLO calculation in on-shell and MS-bar schemes (difference is higher order, but numerically significant)

$$pp \rightarrow b\bar{b}h$$



Scale dependence

Conclusions

- Goal: Try to assess theoretical errors on Higgs production rates in SM
- Can you say anything about new physics from rates alone?